Final Report: Modeling and Observational Study of the Global Atmospheric Impacts of Antarctic Sea Ice Anomalies

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A combined observational and modeling study considers the linkage between Antarctic sea ice and the climate of non-local latitudes. The observational component is based upon analyses of monthly station observations and the National Centers for Environmental Prediction (NCEP)/National Center for Atmospheric Research (NCAR) Reanalysis (NNR). The modeling component consists of simulations of the NCAR Community Climate Model versions 2 (CCM2) and 3 (CCM3) and the recent Community Atmosphere Model (CAM2). A convenient mechanism for communication between the Antarctic region (particularly the Ross Sea area) and the tropics and Northern Hemisphere is examined. The first evidence of this teleconnection came from CCM2 simulations performed during an earlier NASA supported project (Bromwich et al. 1998a,b). Annual-cycle simulations with and without Antarctic sea ice show statistically-significant responses in monsoon precipitation over central and northern China during the month of September. The changes in monsoon precipitation are physically consistent with an intensified southwest Pacific (Northern Hemisphere) subtropical high in response to all Antarctic sea ice being removed and replaced with open water at -1.9°C. The intensified high is the northernmost component of three primary anomalies. The southernmost anomaly includes the Ross Sea area, where sea ice has been removed. An earlier study by Peng and Domrös (1987) had also found a link between Antarctic sea ice and the East Asian monsoon circulation. The current project has helped to understand the teleconnection.

Spurious high southern latitude trends in the NCEP/NCAR Reanalysis

Routine quality control of data used for the observational study detected long-term of trends in the high southern latitude fields of the NNR. Ambitious, detailed reanalyses of many global meteorological fields have been performed by several organizations (Kalnay et al. 1996; Gibson et al. 1997; Higgins et al. 1996). One of the primary motivations for these ambitious projects is reducing the climate jumps believed to be included in previous operational analyses due to many model updates. To achieve this aim, the same "frozen" data assimilation system is used over the entire reanalysis time period. The NNR has produced globally analyzed meteorological fields covering the late 1940s until present. Realistically, it was possible that sufficient observational data existed for useful analyses in the Southern Hemisphere beginning with the International Geophysical Year (1957). The current study, however, has shown that an uneven data record, in combination with model biases, can also facilitate climate jumps and artificial trends in the analyzed fields. As an example, the NNR was found to include a spurious jump increase in the pressure field over China during the mid 1970s. This was of interest to us as precipitation over China responds to the phases of the teleconnection.

Of particular importance to our studies, spurious long-term surface pressure reductions are apparent south of 40°S. The largest trend in surface pressure is near 65°S, in the region of seasonal Antarctic sea ice. There the NNR surface pressure falls by about 10 hPa from 1949 to 1998. Observations, however, do not support this trend. Based upon these findings, we restricted our use of the NNR to the years beginning in 1977. Additionally, the surface pressure field was detrended south of 40°S to minimize the impact of the trend, which was found to continue up to the year 1998. Spurious temporal variability in the NNR is discussed by Hines et al. (2000) in a frequently referenced paper for the *Journal of Climate*. The reporting of the spurious trends has provided critical guidance to researchers interested in studies of high latitude climate with reanalysis products.

Late austral winter teleconnection in the western Pacific Basin

Observational studies have helped to explain how changes in the climatic forcing at high southern latitudes are connected to the tropics and the Northern Hemisphere. In the first year of this project an observed linkage was found to be manifested through a late boreal summer teleconnection. An in-depth discussion of the phenomenon is given by Hines and Bromwich (2002) in an article published in *Journal of Geophysical Research*. The teleconnection is denoted by three primary anomalies in the monthly-average surface pressure field: (i) A high southern latitude component including Wilkes Land, Antarctica, the nearby Southern Ocean and the Ross Sea, (ii) a Southern Hemisphere middle-latitude component near Australia and New Zealand, and (iii) a Northern Hemisphere subtropical component over the extreme western Pacific Ocean (Fig. 1). Surface pressure for the Southern Hemisphere high-latitude anomaly is negatively correlated to that of the other two primary anomalies. The middle-latitude and subtropical components are positively correlated for surface pressure. An index was defined to quantify the amplitude and phase of the teleconnection. A detailed analysis of the day-to-day meteorological fields during the second year of the project showed that the teleconnection is linked with oscillations in tropical convection on the intraseasonal time scale (Hines and Bromwich 2002). *A key consideration to be addressed was the location of the forcing. The observations suggested the teleconnection could be forced in the tropics by intraseasonal oscillations. The earlier CCM2 work, on the other hand, indicated high latitude forcing. Simulations with CCM3 were to be used to address the forcing question.*

CCM3 studies

The linkage between high southern latitudes, the tropics and the Northern Hemisphere is addressed with CCM3 simulations. The NCAR CCM3 has reduced biases both globally and in the western Pacific sector compared to the earlier CCM2 (Kiehl et al. 1998). Yet, several key model biases in the polar regions are noted by Briegleb and Bromwich (1998a,b). For an improved CCM3 simulation of the Antarctic climate two improvements were implemented. Our colleague Von Walden of the University of Idaho has verified that the Rapid Radiative Transfer Model (RRTM, Mlawer et al. 1997; Iacono et al. 2000) alleviates the clear-sky longwave bias (see the web page at http://polarmet.mps.ohio-state.edu/walden/rrtm_verify.html). We obtained a version of the RRTM code from Michael Iacono of AER, Inc. suitable for inclusion in CCM3 simulations.

The prognostic cloud condensate scheme of Rasch and Kristjánsson (1998) has also been included in our version of CCM3, along with RRTM. They developed a new global cloud parameterization in which the standard diagnostic cloud condensate scheme of the NCAR climate models is replaced with a more sophisticated predictive scheme. The standard scheme prescribed the vertical distribution of cloud mass, thus resulting in thick clouds within the Antarctic boundary layer. Rasch and Kristjánsson reported encouraging results for the polar regions in their simulations as the seasonal cycle of cloud amount was found to be improved in the Arctic. Phil Rasch of NCAR supplied a version of the prognostic cloud scheme for CCM3. The changes we have included here are reflective of the direction of the NCAR climate modeling community as the prognostic cloud condensate scheme is now included in the next generation NCAR Community Atmosphere Model (CAM2, Collins et al. 2003). The new model CAM2, however, does not include RRTM. It does include a new longwave scheme with improved radiative properties comparable to those of RRTM (Collins et al. 2002).

Good simulations of both tropical variability and high latitude climate are the logical requirements for us to reasonably simulate the teleconnection between the Antarctic region and the tropics. Unfortunately, important deficiencies are found for both regions in the CCM3 simulations. The deficiencies in the polar regions are, perhaps, not surprising given that many common modeling parameterizations are designed for other (e.g., Pinto and Curry 1997; Randall et al. 1998). This is particularly true for the hydrologic cycle (e.g., Hines et al. 1997). It was anticipated the inclusion of RRTM and prognostic cloud water would reduce the biases in the polar clouds and radiation noticed by Briegleb and Bromwich (1998a). The inclusion of prognostic cloud water qualitatively improved the vertical distribution of cloud condensate over Antarctica (Hines et al. 2003a). *Unfortunately, our revised version of CCM3 did not, in general, simulate an improved climate for Antarctica.* Cloud thickness, along with longwave and shortwave cloud forcing, are excessive over Antarctica in the revised CCM3. The errors in the cloud treatment proved to be larger than the impact of including RRTM, thus the latter had only a minor effect on the simulations. The standard, unmodified version of CCM3 actually simulates a realistic wintertime surface temperature, although the vertical temperature profile in the boundary layer is unrealistic. The modified CCM3, on the other hand, simulates surface temperatures as much as 10°C too warm during winter (Hines et al. 2003a). Furthermore, for all versions of CCM3, there is a large cold bias for the Antarctic tropopause. Also, CCM3 has a summertime cold bias of a few degrees at the surface, as the surface shortwave radiation is much too small during summer. Many of the simulation errors apparently result from the excessive cloud thickness. In order to thin the clouds and improve the simulations, we ran sensitivity simulations that facilitated easier autoconversion of cloud ice to snow over Antarctica. The changes successfully thinned the clouds and reduced some of the radiation biases (Hines et al. 2003a). Another difficulty was then found, as few global climate models are able to properly resolve the extremely thin Antarctic surface boundary layer (e.g., King 1990; Cassano et al. 2001). During winter, the insufficient vertical resolution contributes to an excessive magnitude for the turbulent heat flux downward to surface. This surface heating must then be balanced by excessive longwave cooling. The spurious balance impacts the temperature structure in the simulated boundary layer. Thus, the winter surface temperatures are still too warm, even if the clouds are thinned. *In summary, further model development work is required if an improved Antarctic climate is to be simulated.*

The climate modelers at NCAR are aware of deficiencies in the simulation of polar clouds. We have collaborated with Phil Rasch of NCAR on our work with polar clouds. A new version (2.X) of the current NCAR atmospheric model CAM2 has been developed at NCAR, but not yet publicly released. Several key improvements to the simulation of polar clouds and climate were discussed at the Eighth Annual CCSM Workshop in Breckenridge during June

2003. The improved model formulation now includes a fall speed for cloud particles. Our study of Antarctic clouds helped inspire the model development.

CAM2 studies of the teleconnection

To best capture the intraseasonal tropical component of the teleconnection, adjustments are needed to the NCAR climate models. On the advice of Eric Maloney of Oregon State University and NCAR, we employed the new NCAR CAM2, with T42 horizontal resolution and 26 levels in the vertical, for this work. The CAM2 includes the Collins (2001) scheme to allow a greater variety of cloud overlap assumptions, new water vapor absorptivity and emissivity, improved representations of ozone and topography, and evaporation of precipitation (Collins et al. 2003). Previously, Maloney and Hartmann (2001) had examined tropical intraseasonal variability in the NCAR CCM3. The tropical intraseasonal component is a key feature of the teleconnection (Hines and Bromwich 2002). Maloney and Hartmann, however, found that the Zhang and McFarlane tropical convection scheme in standard CCM3 does not well represent the intraseasonal variability in tropical convection. On the other hand, the older Hack (1994) scheme in CCM2 produced much better results. This may explain the success of the earlier CCM2 results (Bromwich et al. 1998a). Our CCM3 experiments with the Zhang and McFarlane scheme had difficulty producing a representation of the teleconnection. Maloney and Hartmann show the intraseasonal motions are reasonably well simulated, however, if the relaxed Arakawa-Schubert convection scheme is introduced into the NCAR atmospheric model. Eric Maloney has supplied us with a version of the relaxed Arakawa-Schubert scheme that can be implemented into CAM2. Two 15-year simulations are performed with the modified version of CAM2 (Hines et al. 2003b).

The first simulation is a control with climatological boundary conditions; the second simulation replaces all Antarctic sea ice with open water at -1.8°C. Northern Hemisphere sea ice and the Antarctic ice shelves are retained. These CAM2 simulations are similar those performed by Bromwich et al. (1998a) with CCM2. In both the CCM2 and CAM2 cases, the specified forcing is located in high southern latitudes. The new simulations, however, have a much improved treatment of the tropical convection compared to the standard versions of CCM3 and CAM2. Figure 2 shows the surface pressure difference pattern between the simulation without Antarctic sea ice and the control during July. Statistically-significant differences, according to the Student's t-test, are hatched. With CAM2, the sea ice removal results in a general pressure increase near Antarctic latitudes. Conversely, the opposite local response was found by Bromwich et al. (1998a) with CCM2 simulations. Figure 2 also suggests that a NH subtropical component, similar to that of the teleconnection described by Hines and Bromwich (2002), is present as there is reduced pressure anomaly located offshore of China. The magnitude of the anomaly, however, is not large enough to be confirmed as statistically significant. On the other hand, there is a statistically significant anomaly located in the extreme northern Pacific region of the Northern Hemisphere. Figure 1 displays a similar anomaly for August observations, although the phase of the teleconnection is reversed. This feature is also present in the CAM2 simulations during August (Hines et al. 2003b), when observations suggest that the teleconnection is most likely to occur (Hines and Bromwich 2002). Thus, there is evidence that a similar teleconnection to that observed during late boreal summer can be found in a more advanced numerical model with an improved treatment of the tropical intraseasonal motions. Improvements, however, are still needed in the treatment of polar climate to properly treat the polar-tropical interactions. Simulations with CAM2 show a very large warm bias at the surface during winter, due to reasons similar to those for the modified CCM3. Furthermore, the CAM2 simulations show a surface warm bias during summer, as the surface albedo is smaller than in CCM3 simulations or observations (Hines et al. 2003a).

Conclusions

A teleconnection across the western Pacific region during late austral winter is documented in observations. Simulations of the NCAR CCM3 and CAM2 are conducted to study this teleconnection, which was represented in earlier CCM2 simulations (Bromwich et al. 1998a). For an improved CCM3 simulation of the Antarctic climate, we implemented the RRTM longwave radiation code and the Rasch and Kristjánsson (1998) prognostic cloud particulate scheme. Good simulations of both tropical variability and high latitude climate are the logical requirements for us to reasonably simulate the teleconnection between the Antarctic region and the tropics. Unfortunately, important deficiencies are found for both regions in the CCM3 and CAM2 simulations. Tropical intraseasonal variability, which is critical for the teleconnection, can be improved by implementing the relaxed Arakawa-Schubert convection scheme. On the other hand, it was demonstrated that CCM3 and the public version of CAM2 have significant biases in the simulation of Antarctic climate. The changes to the model configuration implemented for this project were unable to facilitate an improved Antarctic climate. A new, unreleased version of CAM2 at NCAR, however, has adjustments to the cloud parameterization and is reported to significantly alleviate biases in the polar simulation. Our modeling studies helped inspire the recent model development. Nevertheless, a reflection of the teleconnection was suggested in simulations of CAM2 with the polar biases and with improved tropical intraseasonal variability.

References

Briegleb, B.P., and D.H. Bromwich, 1998a: Polar radiation budgets of the NCAR CCM3. *J. Climate*, **11,** 1246-1269.

Briegleb, B.P., and D.H. Bromwich, 1998b: Polar climate simulation of the NCAR CCM3. *J. Climate*, **11,** 1270-1286.

Bromwich, D.H., B. Chen, and K.M. Hines, 1998a: Global atmospheric impacts induced by year-round open water adjacent to Antarctica. *J. Geophys. Res.*, **103,** 11,173-11,189.

Bromwich, D.H., B.Chen, K.M. Hines, and R.I. Cullather, 1998b: Global atmospheric responses to Antarctic forcing. *Annals Glaciol.*, **27,** 521-527.

Cassano, J.J., T.R. Parish, and J.C. King, 2001: Evaluation of turbulent flux paramterizations for the stable surface layer over Halley, Antarctica. *Mon. Wea. Rev.*, **129,** 26-46.

Collins, W.D., 2001: Parameterization of generalized cloud overlap for radiative calculations in general circulation models. *J. Atmos. Sci.*, **58,** 3224-3242.

Collins, W.D., J.K. Hackney, and D.P. Edwards, 2002: An updated parameterization for infrared emission and absorption by water vapor in the National Center for Atmospheric Research Community Atmosphere Model. *J. Geophys. Res.*, **107,** doi:10.1029/2001JD001365.

Collins, W.D., J.J. Hack, B.A. Boville, P.J. Rasch, D.L. Williamson, J.T. Kiehl, B. Briegleb, J.R. McCaa, C. Bitz, S.-J. Lin, R.B. Rood, M. Zhang, and Y. Dai, 2003: Description of the NCAR Community Atmosphere Model (CAM2). *NCAR Tech. Note*, in press.

Gibson, J. K., P. Kållberg, S. Uppala,, A. Hernandez, A. Nomura, and E. Serrano, 1997: ECMWF re-analysis project report series. Part 1. ERA description. ECMWF, Shinfield Park, Reading, RG2 9AX, 72 pp.

Hack, J.J., 1994: Parametrization of moist convection in the National Center for Atmospheric Research Community Climate Model (CCM2). *J. Geophys. Res.*, **99,** 5551-5568.

Higgins, R.W., Y.-P. Yao, M. Chelliah, W. Ebisuzaki, J.E. Janowiak, C.F. Ropelewski, and R.E. Kistler, 1996: Intercomparison of the NCEP/NCAR and the NASA/DAO Reanalyses (1985-1993). NCEP/Climate Prediction Center, Atlas No. 2. U. S. Department of Commerce.

Hines, K.M., D.H. Bromwich, and R.I. Cullather, 1997: Evaluating moist physics for Antarctic mesoscale simulations. *Annals Glaciol.*, **25,** 282-286.

Hines, K.M., D.H. Bromwich, and G.J. Marshall, 2000: Artificial surface pressure trends in the NCEP/NCAR Reanalysis over the Southern Ocean and Antarctica. *J. Climate*, **13,** 3940-

3952.

Hines, K.M., and D.H. Bromwich, 2002: A pole to pole West Pacific atmospheric teleconnection during August. *J. Geophys. Res.*, **107,** doi:10.1029/2001JD001335.

Hines, K.M., D.H. Bromwich, P.J. Rasch and M.J. Iacono, 2003a: Antarctic clouds and radiation within the NCAR climate models. *J. Climate*, in press.

Hines, K.M., C.C Hennon, and D.H. Bromwich, 2003b: Antarctic sea ice and a West Pacific teleconnection in the NCAR Community Atmosphere Model. Preprints, *8th Conference on Polar Meteorology and Oceanography*, Hyannis, MA, CD-ROM.

Iacono, M.J., E.J. Mlawer, S.A. Clough, and J.-J. Morcrette, 2000: Impact of an improved longwave radiation model, RRTM, on the energy budget and thermodynamic properties of the NCAR Community Climate Model, CCM3. *J. Geophys. Res.*, **105,** 14,873-14,890.

Kalnay, E., and Coauthors, 1996: The NMC/NCAR 40-year reanalysis project. *Bull. Amer. Meteor. Soc.*, **77,** 437-471.

Kiehl, J.T., J.J. Hack, G.B. Bonan, B.A. Boville, D.L. Williamson, and P.J. Rasch, 1998: The National Center for Atmospheric Research Community Climate Model: CCM3. *J. Climate*, **11,** 1131-1149.

King, J.C., 1990: Some measurements of turbulence over an Antarctic ice shelf. *Quart. J. Roy. Meteor. Soc.*, **116,** 379-400.

Maloney, E., and D. Hartmann, 2001: The sensitivity of intraseasonal variability in the NCAR CCM3 to changes in convective parameterization. *J. Climate*, **14,** 2015-2035.

Mlawer, E.J., S.J. Taubman, P.D. Brown, M.J. Iacono, and S.A. Clough, 1997: Radiative transfer for inhomogeneous atmospheres: RRTM, a validated correlated-k model for the longwave. *J. Geophys. Res.*, **102,** 16,663-16,682.

Peng, G., and M. Domrös, 1987: Connections of the West Pacific Subtropical High and some hydroclimatic regimes in China with Antarctic ice-snow indices. *Meteorol. Atmos. Phys.*, **37,** 61-71.

Pinto, J.O. and J.A. Curry, 1997: Role of radiative transfer in the modeled mesoscale development of summertime arctic stratus. *J. Geophys. Res.*, **102,** 13,861-13,872.

Randall, D., J. Curry, D. Battisti, G. Flato, R. Grumbine, S. Hakkinen, D. Martinson, R. Preller, J. Walsh, and J. Weatherly, 1998: Status of and outlook for large-scale modeling of atmosphere-ice-ocean interactions in the Arctic. *Bull. Amer. Meteor. Soc.*, **79,** 197-219.

Rasch, P.J., and J. Kristjánsson, 1998: A comparison of the CCM3 model climate using diagnosed and predicted condensate. *J. Climate*, **11,** 1587-1614.

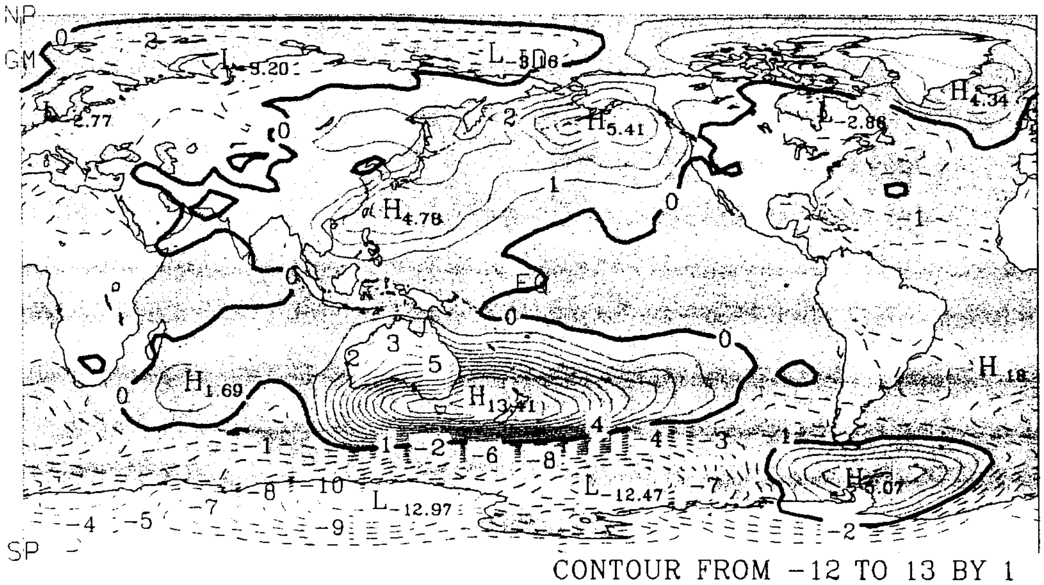

Figure 1. Map of difference in average surface pressure (hPa) of the NCEP/NCAR Reanalysis between 5 Augusts of above average pressure and 5 Augusts of below average surface pressure at 40°S, 145°E. Contour interval is 1 hPa.

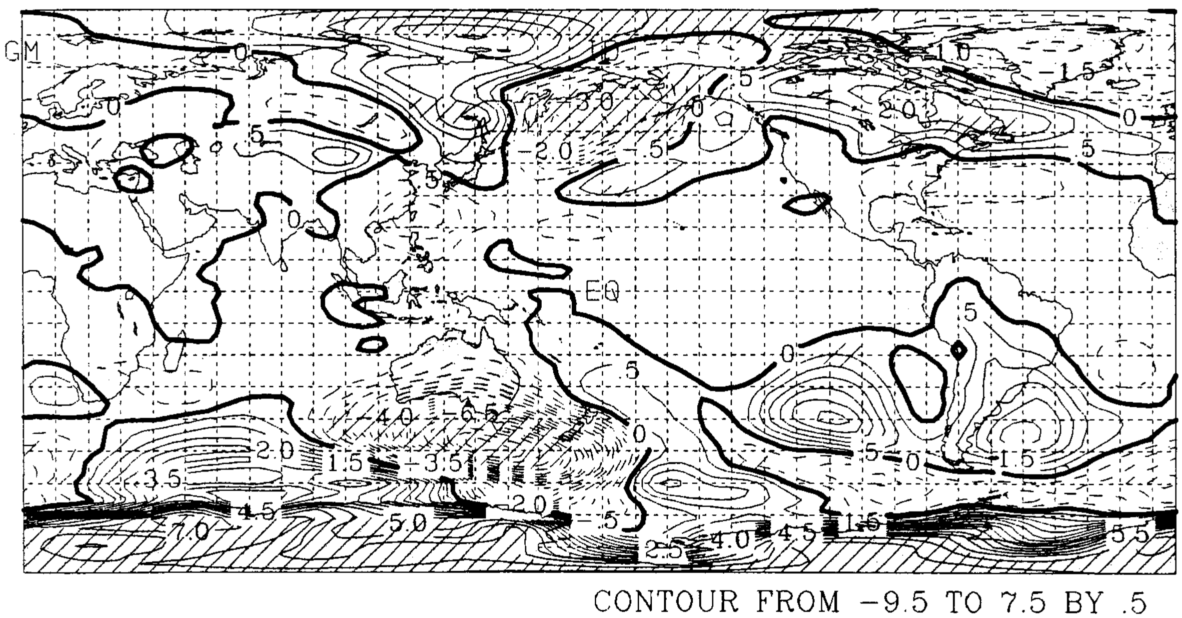

Figure 2. Map of difference in average surface pressure (hPa) between the CAM2 simulation without Antarctic sea ice and the control for July. Contour interval is 0.5 hPa.

Refereed Publications Resulting from NAG5-7750:

Hines, K.M., D.H. Bromwich, and G.J. Marshall, 2000: Artificial surface pressure trends in the NCEP/NCAR Reanalysis over the Southern Ocean and Antarctica. *J. Climate*, **13,** 3940-3952.

Hines, K.M., and D.H. Bromwich, 2002: A pole to pole West Pacific atmospheric teleconnection during August. *J. Geophys. Res.*, **107,** doi:10.1029/2001JD001335.

Hines, K.M., D.H. Bromwich, P.J. Rasch and M.J. Iacono, 2003: Antarctic clouds and radiation within the NCAR climate models. *J. Climate*, in press.

Other Publications Resulting from NAG5-7750:

Hines, K.M., D.H. Bromwich, M.J. Iacono, and P.J. Rasch, 2003: Antarctic Clouds and climate in the NCAR Climate Models. Preprints, *Seventh Conference on Polar Meteorology and Oceanography*, Hyannis, MA, CD-ROM.

Hines, K.M., C.C Hennon, and D.H. Bromwich, 2003: Antarctic sea ice and a West Pacific teleconnection in the NCAR Community Atmosphere Model. Preprints, *Seventh Conference on Polar Meteorology and Oceanography*, Hyannis, MA, CD-ROM.

Bromwich, D.H., and K.M. Hines, 2001: Polar-tropical interactions involving the Ross Sea Sector of Antarctica. Preprints, *Sixth Conference on Polar Meteorology and Oceanography*, San Diego, CA, Amer. Meteor. Soc., J1-J4.

Hines, K.M., and D.H. Bromwich, 2001: Intraseasonal development of a West Pacific pole to pole teleconnection during late austral winter. Preprints, *Sixth Conference on Polar Meteorology and Oceanography*, San Diego, CA, Amer. Meteor. Soc., 73-76.

Hines, K.M., M.J. Iaconno, P.J. Rasch, and D.H. Bromwich, 2001: A global climate modeling study of Antarctic cloud radiative processes. Preprints, *Sixth Conference on Polar Meteorology and Oceanography*, San Diego, CA, Amer. Meteor. Soc., 282-284.

Hines, K.M., D.H. Bromwich, and L. Zhang, 2000: A West Pacific teleconnection pattern between Wilkes Land, Antarctica and the East Asian monsoon during August. Preprints, *Sixth International Conference on Southern Hemisphere Meteorology and Oceanography*, Santiago, Chile, Amer. Meteor. Soc., 376-377.

Hines, K.M., and D.H. Bromwich, 1999: Artificial surface pressure trends in the NCEP/NCAR Reanalysis over the Southern Ocean. Preprints, *Proceedings of the Second International Conference on Reanalyses*, Reading, United Kingdom, European Centre for Medium-Range Weather Forecasts.

Hines, K.M., and D.H. Bromwich, 1999: The roles of Arctic and Antarctic sea ice in forcing global climate. Preprints, *Fifth Conference on Polar Meteorology and Oceanography*, Dallas, TX, Amer. Meteor. Soc., 39-43.